

Hazard Profile – Volcano

Introduction^{1, 2, 3, 4}

A volcano is a vent in the earth's crust through which magma, rock fragments, gases, and ash are ejected from the earth's interior. Over time, accumulation of these erupted products on the earth's surface creates a volcanic mountain.

Washington State has five major volcanoes in the Cascade Range – Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens and Mount Adams.

Volcanoes can lie dormant for centuries between eruptions, and the risk posed by volcanic activity is not always apparent. When Cascades volcanoes do erupt, high-speed avalanches of hot ash and rock called pyroclastic flows, lava flows, and landslides can devastate areas 10 or more miles away, while huge mudflows of volcanic ash and debris called lahars can inundate valleys more than 50 miles downstream. Falling ash from explosive eruptions can disrupt human activities hundreds of miles downwind, and drifting clouds of fine ash can cause severe damage to the engines of jet aircraft hundreds or thousands of miles away.

Washington's volcanoes will erupt again, but none show signs of imminent activity. Because people are moving into areas near these mountains at a rapid pace, the state's volcanoes are among the most dangerous in the United States.

- Mount Baker in Whatcom County erupted in the mid-1800s for the first time in several thousand years. Activity at steam vents in Sherman Crater, near the volcano's summit, increased in 1975 and is still vigorous, but there is no evidence that an eruption is imminent.
- Glacier Peak in Snohomish County has erupted at least six times in the past 4,000 years. An especially powerful series of eruptions about 13,000 years ago deposited volcanic ash at least as far away as Wyoming.
- Mount Rainier in Pierce County is one of the most hazardous volcanoes in the United States. It has produced at least four eruptions and numerous lahars in the past 4,000 years. It is capped by more glacier ice than the rest of the Cascades volcanoes combined, and Rainier's steep slopes are under constant attack from hot, acidic volcanic gases and water. These factors make this volcano especially prone to landslides and lahars. More than 150,000 people live on former lahars in river valleys below the volcano.
- Mount St. Helens in Skamania County is the most frequently active volcano in the Cascades. During the past 4,000 years, it has produced many lahars and a wide variety of eruptive activity, from relatively quiet outflows of lava to explosive eruptions much larger than that of May 18, 1980.

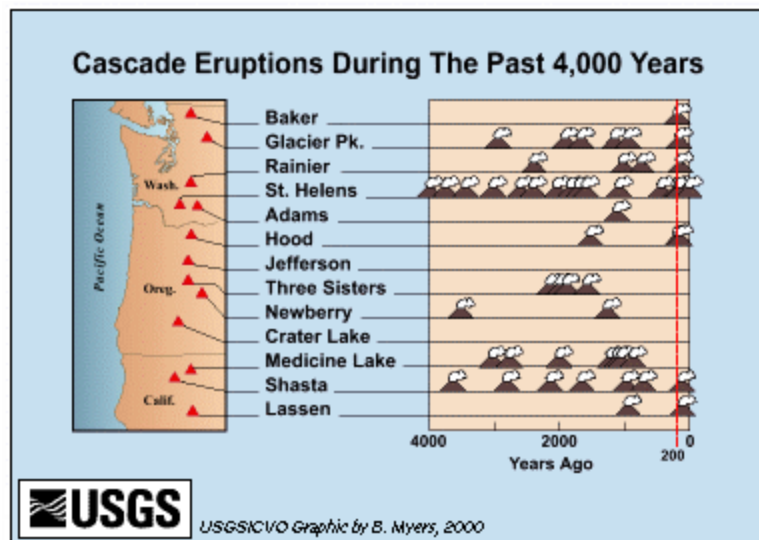
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- Mount Adams in Yakima County has produced few eruptions during the past several thousand years. This volcano's most recent activity was a series of small eruptions about 1,000 years ago.

Additionally, Oregon's Mount Hood, about 50 miles southeast of Portland, poses some threat to areas of Southwest Washington along the Columbia River. Mount Hood has erupted repeatedly for thousands of years, most recently during two episodes in the past 1,500 years; the last eruption ended shortly before the arrival of Lewis and Clark in 1805. Mount Hood, and other volcanoes in British Columbia, Oregon, and California, can produce tephra that would fall on and affect Washington.

The Hazard

Scientists define a volcano as active if it has erupted in historic time or is seismically or geothermally active. Volcanoes commonly repeat past behavior. They usually exhibit warning signs detectable by instruments or observations before they erupt. However, explosions caused by heated material that contacts groundwater, or collapse of one side of the volcano, could occur without warning. Among the effects of volcanic activity:



- Avalanches of glacial ice, snow, rock and debris from volcanic mountains cause damage down slope and in valleys. Such avalanches can range in size from small movements of loose debris on the surface of a volcano to massive failures of the entire summit or flanks of a volcano such as occurred during the 1980 eruption of Mount St. Helens. They travel rapidly and carry large amounts of material; many occur with little or no warning.
- Lahars originate from landslides of water-saturated debris, from the sudden melting of snow and ice, from heavy rainfall eroding volcanic deposits, or from an outbreak of floodwater from a glacier or from lakes dammed by volcanic eruption. Lahars move faster on the steep slopes nearest their source, attaining speeds up to 40 miles per hour; they can travel more than 50 miles downstream. Close to the volcano, lahars have the strength to rip huge boulders, trees, and buildings from the ground and carry them down valley. Farther downstream, they can entomb everything in their path in mud. Historically, lahars have been one of the most deadly volcanic hazards.⁵

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- Tephra falls are from explosive eruptions that blast fragments of rock and ash into the air. Large fragments fall to the ground close to the volcano. Small fragments and ash can travel thousands of miles downwind and rise thousands of feet into the air. In some cases, ash can harm the human respiratory system. Heavy ash fall can create darkness. Ash can clog waterways and machinery, cause electrical short circuits, drift into roadways, railways, and runways. Ash harms mechanical and electronic equipment, and can cause jet engines on aircraft to stall. The weight of ash, particularly when it becomes water saturated, can cause structural collapse. Ash carried by winds can be a hazard to machinery and transportation systems for months after an eruption.
- Lava erupted from vents can form lava flows or steep-sides lava domes. Cascade Range lava flows are relatively short, seldom reaching more than 10 miles from the source, and slow moving. The heat of lava flows can melt ice and snow, creating lahars, or start forest or grass fires. They can bury roads and escape routes. Lava domes extruded on steep slopes are subject to collapse, which is one way a pyroclastic flow forms.
- Pyroclastic flows are high-speed avalanches of hot ash, rock fragments, and gas that move down the sides of a volcano during explosive eruptions or when the steep edge of a lava dome breaks apart and collapses. These flows, which can reach 1,500 degrees F and often move up to 100-150 miles per hour, are capable of knocking down and burning everything in their paths. Pyroclastic flows from Cascade volcanoes rarely travel more than 5 to 10 miles from vents. A pyroclastic surge, a more energetic and dilute mixture of searing gas and rock fragments, also travels very fast. Pyroclastic surges move easily up and over ridges, while flows tend to follow valleys.⁶

Long-term, a volcanic eruption can affect an area in a number of ways, including clogging rivers and streams on the volcano's flank with sediment from lahars and other eruption debris. Transported sediment can affect watersheds for years and decades by reducing their capacity to carry floodwaters, inhibiting their ability to recover, destabilizing their banks, and filling navigable shipping channels. A recent study shows continued movement of large amounts of sediment through the watersheds below Mount St. Helens 20 years after its 1980 eruption.

Past Hazard Events: May 1980 Eruption of Mount St. Helens

Introduction⁷

Mount St. Helens, in southwestern Washington about 40 miles northeast of Vancouver, is one of five volcanic peaks that dominate the Cascade Range in Washington State.

Geologists call Mount St. Helens a composite volcano, or stratovolcano, a term for steep-sided, often symmetrical cones constructed of alternating layers of lava flows, ash, and other volcanic debris. Composite volcanoes tend to erupt explosively and

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pose considerable danger to nearby life and property. In contrast, the gently sloping shield volcanoes, such as those in Hawaii, typically erupt non-explosively, producing fluid lavas that can flow great distances from the active vents. Although Hawaiian-type eruptions may destroy property, they rarely cause death or injury.

Some Indians of the Pacific Northwest variously called Mount St. Helens "Louwala-Clough," or "smoking mountain." Local Indians and early settlers in the region witnessed occasional violent outbursts of the volcano. It was intermittently active from 1831 to 1857. Some scientists also suspect that Mount St. Helens was active sporadically during the three decades before 1831, including a major explosive eruption in 1800.

The mountain gave little or no evidence of being a volcanic hazard for more than a century after 1857. Most people saw Mount St. Helens as a serene, beautiful mountain playground teeming with wildlife and available for leisure activities throughout the year.

The tranquility of the Mount St. Helens region was shattered in the spring of 1980, however, when the volcano stirred from its long repose, shook, swelled, and exploded back to life.

The volcano awakens and erupts⁸

The first sign of activity at Mount St. Helens was a series of small earthquakes that began on March 16. After hundreds of additional earthquakes, steam explosions on March 27 blasted a crater through the summit ice cap. Within a week, the crater had grown to about 1,300 feet in diameter and two giant crack systems crossed the summit area. By May 17, more than 10,000 earthquakes had shaken the volcano and the north flank had grown outward at least 450 feet to form a noticeable bulge. The deformation was evidence that magma had raised high into the volcano.

On May 18, within 15 to 20 seconds of a magnitude 5.1 earthquake at 8:32 a.m., the volcano's bulge and summit slid away in a huge landslide – the largest in recorded history. The landslide depressurized the volcano's magma system, triggering powerful explosions that ripped through the sliding debris. Rocks, ash, volcanic gas, and steam were blasted upward and outward to the north. This lateral blast of hot material accelerated to at least 300 miles per hour, then slowed it spread away from the volcano. The blast cloud traveled as far as 17 miles northward from the volcano and the landslide traveled about 14 miles west down the North Fork Toutle River.

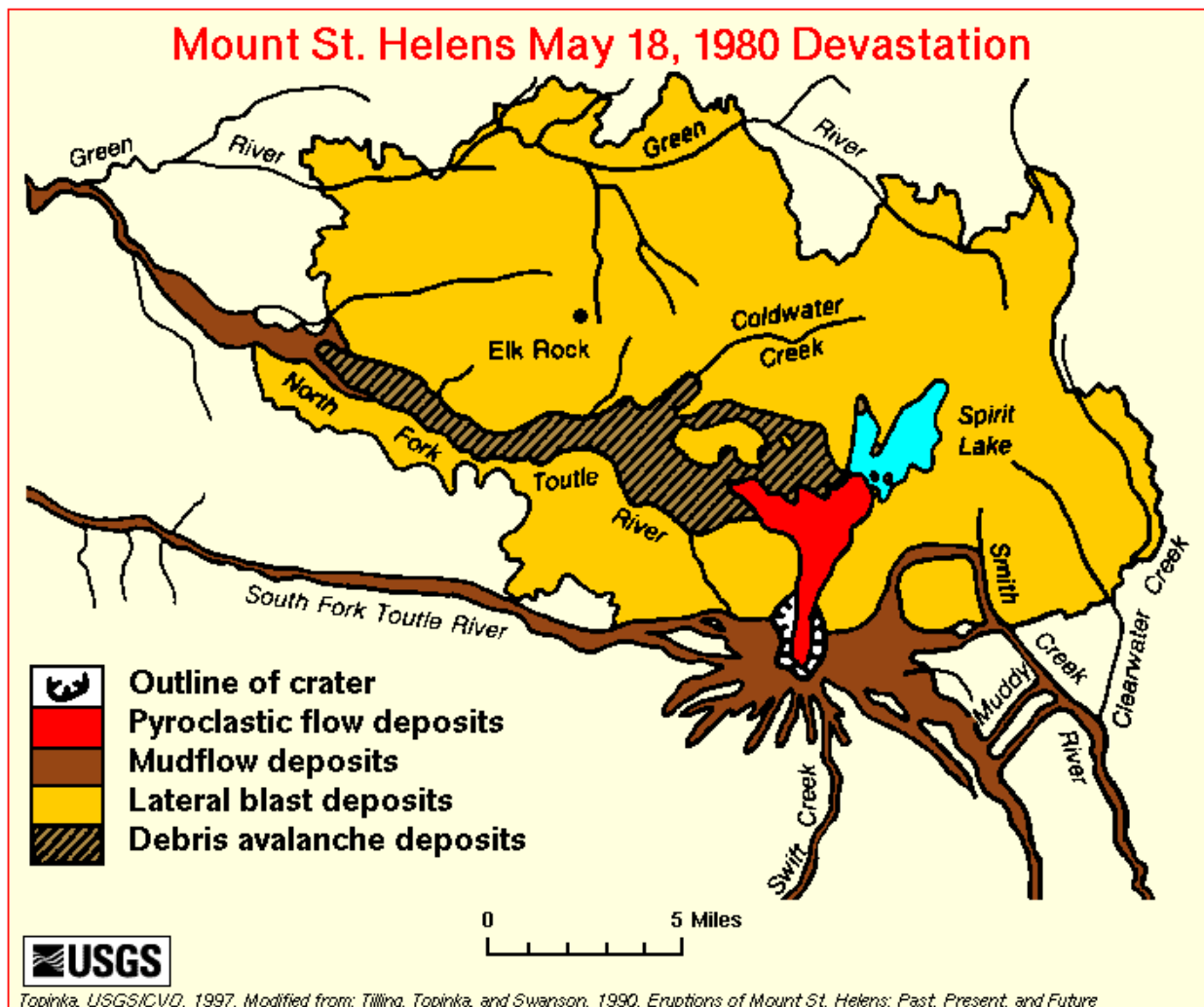
The lateral blast produced a column of ash and gas that rose more than 15 miles into the atmosphere in only 15 minutes. Less than an hour later, a second eruption column formed as magma erupted explosively from the new crater. Then, beginning just after noon, swift avalanches of hot ash, pumice, and gas – pyroclastic flows – poured out of the crater at 50 to 80 miles per hour and spread as far as five miles to the north. Based on the eruption rate of these pyroclastic flows, scientists estimate that the eruption reached its peak between 3 and 5 p.m. Over the course of the day, prevailing winds

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blew 520 million tons of ash eastward across the United States and caused complete darkness in Spokane, 250 miles from the volcano.

During the first few minutes of this eruption, parts of the blast cloud surged over the newly formed crater rim and down the west, south, and east sides of the volcano. The hot rocks and gas quickly melted some of the snow and ice capping the volcano, creating surges of water that eroded and mixed with loose rock debris to form lahars. Several lahars poured down the volcano into river valleys, ripping trees from their roots and destroying roads and bridges.

The largest and most destructive lahar formed by water seeping from inside the huge landslide deposit through most of the day. This sustained flow of water eroded material from both the landslide deposit and channel of the North Fork Toutle River. The lahar increased in size as it traveled downstream, eventually flowing into the Cowlitz River. It reached its maximum size at about midnight in the Cowlitz River about 50 miles downstream from the volcano.



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Five smaller explosive episodes occurred during the summer and fall of 1980. Each produced eruption columns eight to nine miles high and pyroclastic flows down the volcano's north flank. The episodes in June, August, and October also erupted lava in the crater to form a dome. The June and August domes were destroyed by subsequent explosive episodes.

Beginning with the October 1980 eruption, 17 eruptive episodes built a new lava dome that reached 876 feet above the crater floor. Minor explosive activity and lahars accompanied several of these episodes.

In addition to the 17 dome-building episodes, hundreds of small explosions or bursts of gas and steam occurred, sending ash a few hundred feet to several miles above the volcano. The larger explosions showered the crater with rocks and occasionally generated small lahars.

Since late 1986 several periods of increased seismic activity have occurred. Between 1989 and 1991, there were about 30 bursts of brief but intense seismic activity lasting minutes to hours. Small explosions accompanied several of these bursts from the lava dome. The explosions formed a new vent on the north side of the dome and produced small eruption columns that rose a few miles above the volcano. A few explosions also hurled hot rocks three feet in diameter at least one-half mile northward from the dome, generated small pyroclastic flows in the crater, and formed small lahars. During 1995 and 1998, seismic activity increased for several months, but there were no accompanying explosions.

Impact and Aftermath⁹

The May 18, 1980, eruption was the most destructive in the history of the United States; in hours, it caused loss of life and widespread destruction of valuable property.

The eruption resulted in the loss of 57 lives and scores of injuries.

The lateral blast, debris avalanche, mudflows, and flooding caused extensive damage. All buildings near Spirit Lake were buried. More than 200 homes and cabins were destroyed and many more were damaged in Skamania and Cowlitz Counties, leaving many people homeless.

Destroyed or damaged were tens of thousands of acres of prime forest, as well as recreational sites, bridges, roads, and trails, and more than 185 miles of highways and roads and 15 miles of railways.

The lateral blast destroyed or damaged more than 4 billion board feet of salable timber; loggers salvaged about 25 percent of this timber. Wildlife in the Mount St. Helens area suffered heavily.

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Thick ash accumulation destroyed crops downwind of the volcano, while crops in areas blanketed by only a thin covering of ash survived. Effects of the ash on the water quality of streams, lakes, and rivers were short lived and minor.

The ash fall posed temporary but major problems for transportation and for sewage-disposal and water-treatment systems. Because visibility was greatly decreased during the ash fall, many highways and roads were closed to traffic, some only for a few hours, but others for weeks. Interstate 90 from Seattle to Spokane closed for a week. Ash accumulation and poor visibility disrupted air transportation for as much as two weeks as several airports in Eastern Washington shut down. Airport closures caused the cancellation of more than one thousand commercial flights.

The sewage-disposal systems of several municipalities that received a half-inch or more of ash, including Moses Lake and Yakima, were plagued by ash clogging and damage to pumps, filters, and other equipment. Water supply systems using deep wells and closed storage were minimally affected.

The fine-grained, gritty ash caused substantial problems for internal-combustion engines and other mechanical and electrical equipment. The ash contaminated oil systems, clogged air filters, and scratched moving surfaces. Fine ash caused short circuits in electrical transformers, which caused power blackouts.

The removal and disposal of ash from highways, roads, buildings, and airport runways posed a monumental task for some Eastern Washington communities. Workers cleared an estimated more than 2.4 million cubic yards of ash – weighing about 900,000 tons – from highways and airports throughout the state. Ash removal cost \$2.2 million and took 10 weeks in Yakima.

Accurate cost figures of the destruction and damage caused by the May 18 eruption are difficult to determine. Early estimates ranged from \$2 to \$3 billion, primarily reflecting the timber, civil works, and agricultural losses. An International Trade Commission study requested by Congress estimated the loss at \$1.1 billion. Congress voted a supplemental appropriation of \$951 million for disaster relief, the largest shares of which went to the Small Business Administration, U.S. Army Corps of Engineers, and the Federal Emergency Management Agency.

There were indirect and intangible costs of the eruption as well. Unemployment in the region near Mount St. Helens rose tenfold in the weeks following the eruption, nearly returning to normal once timber salvaging and ash-cleanup operations were underway. Only a small percentage of residents left the region because of job loss caused by the eruption. Several months after May 18, a few residents reported suffering stress and emotional problems, even though they had coped successfully during the crisis. The counties in the region requested funding for mental health programs to assist such people.

Initial public reaction to the May 18 eruption nearly dealt a crippling blow to tourism, an important industry in Washington State. Conventions, meetings and social gatherings

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planned for cities and resorts in areas of Washington and neighboring Oregon not affected by the eruption were canceled or postponed. The negative impact on tourism and conventions proved only temporary. Mount St. Helens, perhaps because of its reawakening, has regained its appeal for tourists.

Likelihood of Future Hazard Events and Areas Likely to be Impacted

*Glacier Peak*¹⁰

Glacier Peak has erupted several times since the Ice Age glaciers retreated 15,000 years ago – most recently around the 18th century. Since glacial times, Glacier Peak has had larger and more explosive eruptions than any Washington volcano except Mount St. Helens. Glacier Peak and Mount St. Helens are distinct from other Washington Cascade volcanoes in their tendency to produce large, explosive eruptions that break erupting lava into small fragments and disperse them into the atmosphere.

Lahars represent the greatest hazard, followed by tephra fall.

Lahar:

- Glacier Peak has produced numerous lahars and floods in the past 14,000 years, at least some of which began as pyroclastic flows or surges. Lahars have descended the Suiattle, White Chuck, Sauk, and Skagit River valleys during several eruptive periods. Even the North Fork Stillaguamish River valley, which previously was an outflow route of the Sauk River, has been inundated by Glacier Peak lahars. Two eruptive periods, about 13,000 and 6,000 years ago, repeatedly produced large lahars, some of which reached Puget Sound.
- Collapse of up to one-third of the volcano's structure that lies above 6,000 feet elevation would cause the largest credible lahar. It would reach the Skagit River delta in several hours and cover a significant portion of the Skagit and Sauk floodplains with debris. Below the Sauk-Skagit confluence, the lahar hazard zone covers more than the floodplain. Below the confluence with the Baker River, this hazard zone coincides with the one drawn for lahars from Mount Baker.
- The Stillaguamish River valley potentially could be inundated by a lahar if the river were once again to become the main drainage outflow for Glacier Peak.
- Based on past events, the annual probability for a lahar that extends at least to the lower Suiattle River or to the confluence of the White Chuck and Sauk Rivers is roughly 1 in 1,000 to 1 in 2,000. The annual probability that a lahar would reach Puget Sound is about 1 to 2 in 10,000. The annual probability of lahars inundating the Stillaguamish River valley is thought to be less than 1 in 10,000.

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Tephra:

- Eruptions of Glacier Peak have deposited at least nine layers of tephra near the volcano in postglacial time. By far the thickest deposits were east, southeast, and south of the volcano during a series of powerful eruptions about 13,100 to 12,500 years ago. The average frequency of tephra-producing eruptions is roughly one every 2,000 years.
- Due to prevailing winds, tephra is far more likely to fall on the east side of the volcano within a few tens of miles of the summit than on the west side. No buildings lie within this wilderness area. However, any repetition of the huge eastside tephra accumulations of about 13,100 years ago would cause problems at least as far as Chelan, probably much farther east and likely to communities out of state.

A lateral volcanic blast from Glacier Peak most likely would be smaller than the actual 1980 Mount St. Helens blast zone. Topography would strongly channel a blast flow toward the northwest or southeast, so that it would reach far out only along valleys – farthest to the northwest.

Ballistic projectiles rarely are thrown more than 3 miles from the mountain; but unlike tephra falls, they can be in directions other than downwind.

Pyroclastic-flow deposits about 13,100 to 12,500 years old fill the floor of White Chuck valley at least as far as 6.5 miles northwest of the summit. Pyroclastic-flow and -surge deposits about 5,500 years old on the east volcano flank lie 5 miles from the summit. It is likely these flows went much farther; erosion and burial has hidden some of the evidence.¹¹

Lava flows extend down all flanks from Glacier Peak's summit but nowhere farther than about 6 miles from the summit. Future flows also would be confined to this area. Because the lava-flow zone lies entirely in wilderness, hazards to developed areas from lava flows are all but negligible, though secondary effects such as forest fires could reach developed areas.

In future eruptions, lava flows and ballistic projectiles will probably be contained within 5 to 6 miles of the summit. Pyroclastic flows could travel 13 miles to the west and north of the summit, while pyroclastic surges could travel another three miles farther.

Mount Adams¹²

Mount Adams dominates a volcanic field in Skamania, Yakima, Klickitat, and Lewis counties of south-central Washington. The volcano has erupted little during the past 10,000 years; it is less active than neighboring Mounts St. Helens, Rainier, and Hood. Highly explosive eruptions of Mount Adams have been rare. Much of the hazard area for eruptive events lies in the Gifford Pinchot National Forest or remote areas of the

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Yakima Indian Reservation. Areas of greatest concern are located along the channels and floodplains of rivers subject to lahars.

Lahars:

- Streams that drain the north and northwest flanks of Mount Adams can discharge sediment from lahars into Swift Reservoir on the Lewis River and Riffe Lake on the Cowlitz River. Streams that drain the southwest and east flanks can deliver sediment to the Columbia River and could affect navigation and hydroelectric operations at Bonneville Dam. Impacts on the small reservoir and hydroelectric operation on the White Salmon River could be severe.
- The Trout Lake avalanche and lahar, which occurred in the upper White Salmon River drainage about 6,000 years ago, is the only debris avalanche or lahar that has traveled far (about 35 miles) beyond the volcano flanks in the past 10,000 years.
- A large avalanche-triggered lahar in the White Salmon drainage could bury the Trout Lake lowland, enter the Columbia River, and inundate both the Oregon and Washington shorelines for a considerable distance. A lahar comprising 1 cubic kilometer of debris likely would transport enough sediment to the Columbia to exceed the capacity of usable storage of Bonneville Reservoir and cause overtopping of Bonneville Dam. Consequences of dam overtopping, which might trigger dam failure, could be severe. A large lahar could itself dam the Columbia River, back up water behind it, and fail, with similarly severe results.
- A large lahar in the Klickitat valley could affect the Columbia River, Bonneville Reservoir, and Bonneville Dam in a manner similar to a large lahar in the White Salmon valley.
- Lahars large enough to reach the Trout Lake lowland have annual probabilities of about 1 in 100 to 1 in 1,000. A lahar the size of the Trout Lake lahar has an annual probability of about 1 in 1,000 to 1 in 10,000, whereas a lahar of sufficient magnitude to inundate the length of one or more valleys has not occurred in the last 10,000 years and has an annual probability less than 1 in 10,000.
- Small avalanches or lahars triggered by rainfall, rapid snowmelt, heavy snowfall, or glacier outbursts occur frequently, but seldom travel more than a few miles from their sources on steep volcano flanks. Such events have annual probabilities greater than 1 in 10; they endanger backcountry recreationists and may damage timber, trails and bridges, but not settled areas.
- A number of lakes close to the volcano in the Lewis River and Cowlitz River valleys could play a role in the size of future lahars. Both Swift Reservoir and Riffe Reservoir generally are not at risk to lahar. This assumes, however, that operators of the reservoirs' dams would lower lake levels in advance of an

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imminent eruption – as they did for the May 1980 eruption of Mount St. Helens – and that a lahar reaching the reservoir would not be appreciably larger than those of 1980 would.¹³

The dominant type of eruption at Mount Adams, as well as in the adjacent volcanic fields, produces lava flows, or streams of molten rock. Several significant lava flows have occurred in the region during the past 10,000 years, most traveled between 8 and 20 miles.

Tephra from Mount Adams does not pose a serious hazard; eruptions have blanketed only areas a few miles away with ash fall of several inches thick. Thinner deposits probably extended tens of miles farther. Pyroclastic flows have been rarer at Mount Adams during the past 10,000 years than at other nearby volcanoes.

The probability of a lava flow occurring in a year on Mount Adams itself is about 1 in 1,000; the probability of a larger lava flow that significantly affects a given point in the region surrounding the volcano occurring in a year is about 1 in 30,000 to 1 in 1,000,000, depending on size and location of the flow.

The maximum credible eruption at Mount Adams is an event of very low annual probability, less than 1 in 100,000.

Mount Baker¹⁴

Mount Baker is not showing signs of renewed activity, but will again. The main hazards at Mount Baker are from lahars and debris avalanches. These may occur with or without an accompanying eruption.

Lahars:

- The largest lahar, about 6,800 years ago, probably originated as a large debris avalanche. This flow moved down the Middle Fork of the Nooksack River to the main Nooksack River and can be traced as far downstream as Deming, where younger river deposits have buried it. In all likelihood, this lahar traveled all the way to Puget Sound.

This lahar is a Case M lahar; it has a recurrence interval of about once every 14,000 years.

- Of special concern is a lahar or pyroclastic flow entering Baker Lake, southeast of the mountain, and displacing enough water to either overtop Upper Baker Dam or cause failure of the dam. Either scenario would have consequences for the stability of the dam. If the dam fails, the resulting lahar or flood would most likely affect the entire Skagit River floodplain to Puget Sound. Such a lahar could inundate this zone to a depth of up to 16 feet.

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- A very large lahar, or a series of lahars moving down the Nooksack River, similar to the one that occurred 6,800 years ago, could deposit enough material in the stretch of river between Lynden and Everson to raise the river bed enough to cause flood waters to spill into the Sumas River or to divert the Nooksack River into the Sumas River basin.
- A Case 1 lahar is a non-cohesive debris flow resulting from melting snow and ice from eruptive activity, increased fumarolic heating or steam explosions. This is the most likely event to affect drainages on the north side of the volcano. Such a debris flow affecting the Nooksack River drainage has a projected recurrence rate of about once every 500 years.
- A Case 2 lahar, about the same size as a 100-year flood, are cohesive debris flows from small to moderate debris avalanches from either Sherman Crater or the upper Avalanche Gorge. Such lahars could occur during times of no volcanic activity. Recurrence rate for a case 2 lahar is about once every 100 years. Increased volcanic activity could increase the recurrence intervals for both Case 1 and Case 2 lahars.

Only one episode of pyroclastic-flow and -surge activity is recognized. It took place about 9,600 years ago, with deposits confined to the Boulder Creek valley, southeast of the mountain.

No lateral blast of the magnitude of the 1980 Mount St. Helens event has been recognized at Mount Baker. Such an event is credible, although unlikely. A blast at Mount Baker similar to the 1980 blast at Mount St. Helens could threaten the communities of Glacier, Van Zandt, and Concrete, and perhaps Deming.

Mount Baker has not produced large amounts of tephra in the past and probably will not in the future. Because winds are dominantly from the west, it is likely that any tephra will be carried to the east away from most major communities; for most, the tephra will only be a nuisance. The annual likelihood of one centimeter of tephra falling in eastern Whatcom County, western Okanogan County, and parts of Skagit and Chelan Counties and southern British Columbia is one chance in 50,000.

Mount Rainier^{15, 16, 17}

Mount Rainier – at 14,410 feet the highest peak in the Cascade Range – has more glacier ice than the rest of the Cascade volcanoes combined. This tremendous mass of rock and ice, in combination with great topographic relief, poses a variety of geologic hazards. Most geologic phenomena affect only the immediate vicinity of Mount Rainier; however, lahars and tephra falls could affect great numbers of people far from the volcano.

Lahars:

- During the past 10,000 years, at least 60 lahars have moved down valleys that

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begin at Mount Rainier. Lahars are the greatest threat to communities below the volcano. More than 150,000 people live on deposits of old lahars. Lahars that reached the Puget Sound lowland have occurred about every 500 to 1,000 years, with smaller flows not traveling as far as the lowland occurring more frequently. Scientists believe there is a one in seven chance that a lahar will reach the Puget Sound lowland in the average human lifespan if future lahars occur at rates similar to those of previous lahars.

- Past lahars at Mount Rainier have varied tremendously in size and frequency. For purposes of hazards assessment, there are four classes of lahar. In order of decreasing size and increasing frequency, they are Case M, Case I, Case II, and Case III lahars.
 - Case M lahar: The largest lahar to occur in the past 10,000 years is the Osceola Mudflow. It formed about 5,600 years ago when a massive debris avalanche of weak, chemically altered rock transformed into a lahar. Osceola deposits cover an area of about 212 square miles in the Puget Sound lowland, extending at least as far as Kent and to Commencement Bay in Tacoma. The communities of Orting, Buckley, Sumner, Puyallup, Enumclaw, and Auburn are wholly or partly located on top of deposits of the Osceola Mudflow. This lahar is at least 10 times larger than any other known lahar from Mount Rainier.

A Case M lahar entering Riffe Lake on the Cowlitz River could affect areas downstream in one of two ways:

1. The lake might contain the lahar if the level of the lake behind the dam is lowered and the lahar was small.
2. The lahar could cause the dam to fail or catastrophically displace a significant volume of water to inundate the Cowlitz River valley all the way to the Columbia River at Longview and Kelso.

Geologists believe flows of this magnitude occur far less frequently than once every 1,000 years.

- Case I lahar: These flows, generated by debris avalanches much smaller than the Osceola Mudflow, have occurred on average about once every 500 to 1,000 years during the past 5,600 years. Most Case I flows have reached some part of the Puget Sound lowland. The Electron Mudflow reached the lowland about 600 years ago along the Puyallup River. Its deposits at Orting are as much as 18 feet thick and contain remnants of an old-growth forest.

A Case I lahar occurring today could destroy all or parts of Orting, Sumner, Puyallup, Fife, the Port of Tacoma, and possibly Auburn. Also, a Case I lahar entering Alder Lake on the Nisqually River could affect areas downstream in one of two ways:

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1. The lake might contain the lahar if the level of the lake behind the dam is lowered and the lahar was small.
 2. The lahar could cause the dam to fail or catastrophically displace a significant volume of water to inundate the downstream river valley all the way to Puget Sound near Olympia.
- Case II lahar: These flows, caused by eruptions swiftly melting snow and ice, have an average recurrence interval near the lower end of the 100- to 500-year range. More than a dozen lahars of this type have occurred in the past 6,000 years. A few have reached the Puget Sound lowland, including the National Lahar, which occurred about 2,000 years ago. It inundated the Nisqually River valley to depths of 30 to 120 feet and flowed all the way to Puget Sound. About 1,200 years ago, another lahar filled valleys of both forks of the White River to depths of 60 to 90 feet, and flowed 60 miles to Auburn.

The lower Green and Duwamish River valley could be at significant risk to a Case II lahar or redistribution of new lahar deposits if one of two conditions occurs:

1. The available storage of Mud Mountain Reservoir is reduced significantly by a lahar or post-lahar sedimentation.
 2. The profile of the lower White River valley south of Auburn is changed sufficiently by a lahar or post-lahar sedimentation to cause the White and Puyallup Rivers to drain northward into the Green and Duwamish River valley.
- Case III lahar: These flows are relatively small but occur frequently, every one to 100 years. This class of flows includes small debris avalanches as well as debris flows triggered by sudden, unpredictable release of water stored by glaciers. These debris flows are largely restricted to the slopes of the volcano, rarely moving beyond the National Park boundary; since 1926, outburst floods destroyed or damaged bridges, roads, and national park visitor facilities on about 10 occasions. Glacial outburst floods are unrelated to volcanic activity and typically coincide with periods of unusually high temperatures or unusually heavy rain in summer or early autumn. About three dozen such flows occurred during the 20th century

Lahar Warning System: Because of the higher level of risk from lahars in the Carbon and Puyallup River valleys, the U.S. Geological Survey and Pierce County in the mid 1990s installed lahar detection and warning systems in the valleys just outside the national park. The system consists of arrays of five acoustic flow monitors along each river that detect the ground vibrations of a lahar. Computerized evaluation of data confirms the presence of a flowing lahar and issues an automatic alert to Pierce County and state emergency management agencies; emergency managers then can initiate response measures such as evacuations. This system reduces, but does not eliminate, risk in the lahar pathways.

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The U.S. Geological Survey has estimated travel times for lahars up to 100 million cubic meters, similar in size to a Case I lahar, for both the Puyallup and Carbon River basins (see page 13 for an example of a Case I lahar).

Puyallup River lahar – A lahar originating in the Sunset Amphitheater at the top of the Puyallup Glacier is projected to reach the following communities in the estimated times after the lahar warning system sounds an alarm:

Community	Distance from the Source	Estimated Arrival After Alarm
Orting	32 miles	42 minutes
Sumner	40 miles	65 minutes
Puyallup	43 miles	78 minutes
Auburn	46 miles	96 minutes
Commencement Bay, Tacoma	49 miles	108 minutes

Carbon River lahar – A lahar originating near the middle or upper part of Willis Wall at the top of the Carbon Glacier is projected to reach the following communities in the estimated times after the lahar warning system sounds an alarm:

Community	Distance from the Source	Estimated Arrival After Alarm
Carbonado	24 miles	12 minutes
Wilkeson	27 miles	18 minutes
Orting	32 miles	42 minutes

Larger lahars would reach downstream communities more quickly.

Other hazards:

Tephra: Mount Rainier is a moderate tephra producer relative to other Cascade volcanoes. Eleven eruptions have deposited layers of tephra near the volcano in the past 10,000 years; the average interval between eruptions is about 900 years. Tephra loads of 4 inches or more are most likely to occur east of the mountain, within a few tens of miles of the summit.

Pyroclastic flows: Lack of evidence of pyroclastic flows leads scientists to conclude that most convert to lahars as they pass over snow and ice. Two pyroclastic flows in the past 2,500 years traveled only about seven miles from the volcano.

Ballistic projectiles: They rarely travel three miles from the vent; most projectiles are less than three feet across. The chief hazard from ballistic projectiles is direct impact. Projectiles may still be quite hot when they land, and can start fires if they land near combustible materials.

Hazard Profile – Volcano

In future eruptions, pyroclastic flows and surges, as well as lava flows and ballistic projectiles, probably will not extend beyond the national park boundaries.

Lava flows: Much of Mount Rainier is composed of lava flows. The most serious hazard of lava flows is when they contact snow and ice, creating floods and lahars. The only lava flows known from Mount Rainier in the past 10,000 years are those that built the summit cone, constructed within the past 5,600 years.

The annual probability of pyroclastic flows, surges, lava flows, and ballistic projectiles affecting some part of the area is less than 1 percent.

Lateral blast: On Mount Rainier, at least one laterally directed explosion accompanied the debris avalanche that produced the Osceola Mudflow, as the mountain's hydrothermal system was depressurized. Three factors conducive to such an event – substantial volumes of weak hydrothermally altered rock, substantial topographic relief, and an active hydrothermal system – are present at Mount Rainier.

The Mount Rainier blast-hazard zone extends farthest to the northwest of the volcano because of the lack of high ridges or other topographic barriers in that direction.

Mount St. Helens¹⁸

Mount St. Helens remains a potentially active and dangerous volcano, even though it is now quiet. In the last 515 years, it produced four major explosive eruptions and dozens of lesser eruptions. One of those, in 1480, was about five times larger than the May 18, 1980 eruption; even larger eruptions occurred during Mount St. Helens' geologically brief but very active 50,000-year lifetime.

Among the possibilities for renewed eruptive activity at Mount St. Helens are resumption of dome growth, and eruption of tephra, lava and pyroclastic flows in volumes that could be as large as or even larger than the volume erupted in 1980.

Lahars are a greater threat to life and property in communities of the Cowlitz and lower Toutle River drainages than any other volcanic phenomenon. Previous lahars, including those from the May 18, 1980 eruption, traveled 30 to 60 miles, often reaching the Columbia River via the Toutle, Kalama or Lewis Rivers. Non-eruption events such as intense storm runoff over erodible sediment, landslides, or failure of the Castle Lake impoundment can generate lahars. Neither a large debris avalanche nor a major lateral blast like those of May 1980 is likely now that a deep, open crater has formed.

- The amount of available water limits the maximum size of a potential lahar. Rapid melting of snow and ice in the crater or a sudden outbreak of Castle Lake are the most likely mechanisms to cause a lahar. Either would produce a lahar only in the North Fork Toutle River and downstream. A sufficient volume of permanent and seasonal snow and ice exists in winter or spring on the outer flanks of the volcano to produce lahars similar in magnitude to those of May 18, 1980, if another large eruption were to occur.

Hazard Profile – Volcano

- A number of hydropower reservoirs close to the volcano in the Lewis River valley could play a role in the size of future lahars. The Swift Reservoir and downstream lakes are capable of trapping a lahar and stopping its advance, assuming that operators of the reservoir's dam would lower the lake level in advance of an imminent eruption – as they did in 1980 – and that a lahar reaching the reservoir would not be appreciably larger than those of May 1980.
- The natural dam at Castle Lake could produce a lahar on its own if the blockage were to fail. Overtopping and possible breaching of the Sediment Retention Structure downstream also could result in a significantly larger lahar in the Toutle and Cowlitz Rivers than postulated.
- The Cowlitz River channel at both Kelso and Longview should contain a lahar similar in size to a 100-year flood, but parts of the Toutle River valley between the Sediment Retention Structure and the Cowlitz River could not contain such a lahar.
- Based on the behavior of lahars from the May 1980 eruption, estimated travel times have been developed for lahars traveling down the North Fork Toutle River valley, and the South Fork Toutle River, Pine Creek, Muddy River, and Kalama River valleys:

Distance from Mount St. Helens	Projected Lahar Travel Time	
	N. Fork Toutle River	S. Fork Toutle River Pine Creek Muddy River Kalama River
20 Kilometers (12.4 miles)	37 minutes	30 minutes
40 kilometers (24.9 miles)	1 hour, 8 minutes	1 hour, 21 minutes
60 kilometers (37.3 miles)	3 hours, 27 minutes	2 hours, 20 minutes
80 kilometers (49.7 miles)	4 hours, 43 minutes	3 hours, 31 minutes
100 kilometers (62.1 miles)	8 hours, 50 minutes	5 hours, 12 minutes

Projected recurrence rates for lahars are not available for Mount St. Helens.

Mount St. Helens repeatedly has produced voluminous tephra. While tephra from the May 18, 1980 eruption covered about 22,000 square miles, the lethal impact from falling tephra is likely only in the immediate vicinity of Mount St. Helens; damaging impacts from falling tephra, as described earlier in this profile (see pages 6-7) were seen hundreds of miles away. A larger eruption could cover as much as 40,000 square miles with tephra. Westerly winds prevail, making significant tephra accumulation from a single eruption more likely east of Mount St. Helens.

Hazard Profile – Volcano

The calculated annual probability that four or more inches of tephra from a large eruption will fall as far as 40 miles directly east of Mount St. Helens is about 1 in 500. The calculated annual probability that such an eruption would deposit four or more inches 40 miles directly west of Mount St. Helens is less, between 1 and 2 in 10,000.

Lateral blasts may generate complex pyroclastic flows and surges and launch ballistic projectiles. The current shape of the volcano – with its large crater and much lower summit – makes a landslide and massive laterally directed blast similar in size to the May 18, 1980 blast unlikely when eruptive activity next resumes.

Pyroclastic flows from the May 18, 1980 eruption ran about five miles from the vent. As they impinged on Johnston Ridge, they were deflected westward down valley and eastward to Spirit Lake. During the past 4,000 years in which the volcano's modern edifice formed, numerous pyroclastic flows traveled at least six to nine miles, and at least one older flow traveled up to 12 miles. Although the present crater geometry favors distribution of pyroclastic flows into the North Fork Toutle River valley, all flanks of the volcano are subject to pyroclastic-flow hazard during a large eruption.

Because they are less dense, pyroclastic surges are less constrained by topography than are pyroclastic flows. On May 18, 1980, pyroclastic surges surmounted Johnston Ridge and entered the drainage of South Coldwater Creek, even though the steep north-facing escarpment of the ridge deflected the related pyroclastic flows.

Blasts have launched projectiles from the volcano. A blast related to emplacement of the Sugarbowl dome on the north flank of Mount St. Helens about 1,200 years ago propelled ballistic fragments as large as 2 inches as far as six miles from the vent. More recently, a series of relatively small steam-driven explosions in 1989–91 threw hundreds of blocks, some as large as a yard, for distances of one-half mile from the dome within the Mount St. Helens crater. Similar explosions could occur without warning in the future but become progressively less likely with continued cooling of the dome's hot interior and the subsurface conduit that supplied the magma for dome growth.

Numerous lava flows have issued from Mount St. Helens. A lava flow from a vent in the present crater would be directed down the north flank of Mount St. Helens and possibly into the upper part of the North Fork Toutle River valley. Most have affected only areas within six miles of the summit, but two basalt flows that issued about 1,700 years ago extended about 10 miles from the volcano's summit; one of them, which flowed south to the Lewis River valley east of Cougar, contains the Ape Cave lava tube.

Mount Hood, Oregon¹⁹

Areas of Clark, Skamania and Klickitat Counties are at risk to the impacts of lahars generated by Mount Hood.

Growth and collapse of lava domes dominated eruptive activity at Mount Hood during the past 30,000 years. The last two episodes occurred 1,500 and 200 years ago.

Hazard Profile – Volcano

Repeated collapse of lava domes near the site of Crater Rock, Mount Hood's youngest lava dome, generated pyroclastic flows and lahars and built much of the broad smooth fan on the south and southwest flank of the volcano.

After the last eruptive period, sediment choked the Sandy River, enlarged its delta, and pushed the Columbia River against the Washington shore in the Camas-Washougal area.

More than 100,000 years ago, a much larger debris avalanche and related lahar flowed down the Hood River, crossed the Columbia River, and flowed several kilometers up the White Salmon River in Klickitat County. Scientists believe this deposit dammed the Columbia River at least temporarily.

A future eruption could greatly affect the Columbia River, its shipping channel, and, potentially, hydroelectric installations, such as Bonneville Dam, tens of miles from the volcano.

Future lahars and eruption-induced sedimentation are likely to build the Sandy River delta farther out into the Columbia River and narrow the existing channel, which could lead to progressive bank erosion and inundation of land in the Camas-Washougal area of Clark County. The 30-year probability that lahars will inundate areas of the Sandy River valley is about 1 in 15 to 1 in 30. It is impossible to develop a more specific forecast other than to note that areas close to the rivers and land composed of erodible deposits are the most vulnerable.

Future lahars in the Hood River Valley are less probable than in the Sandy River valley, but lahars entering the Columbia from Hood River could push the Columbia against its north bank and cause bank erosion or inundation in Klickitat and Skamania Counties.

Mount Hood is a relatively modest tephra producer, and much of the tephra fall would occur east of the mountain due to prevailing winds.

Hazard Profile – Volcano

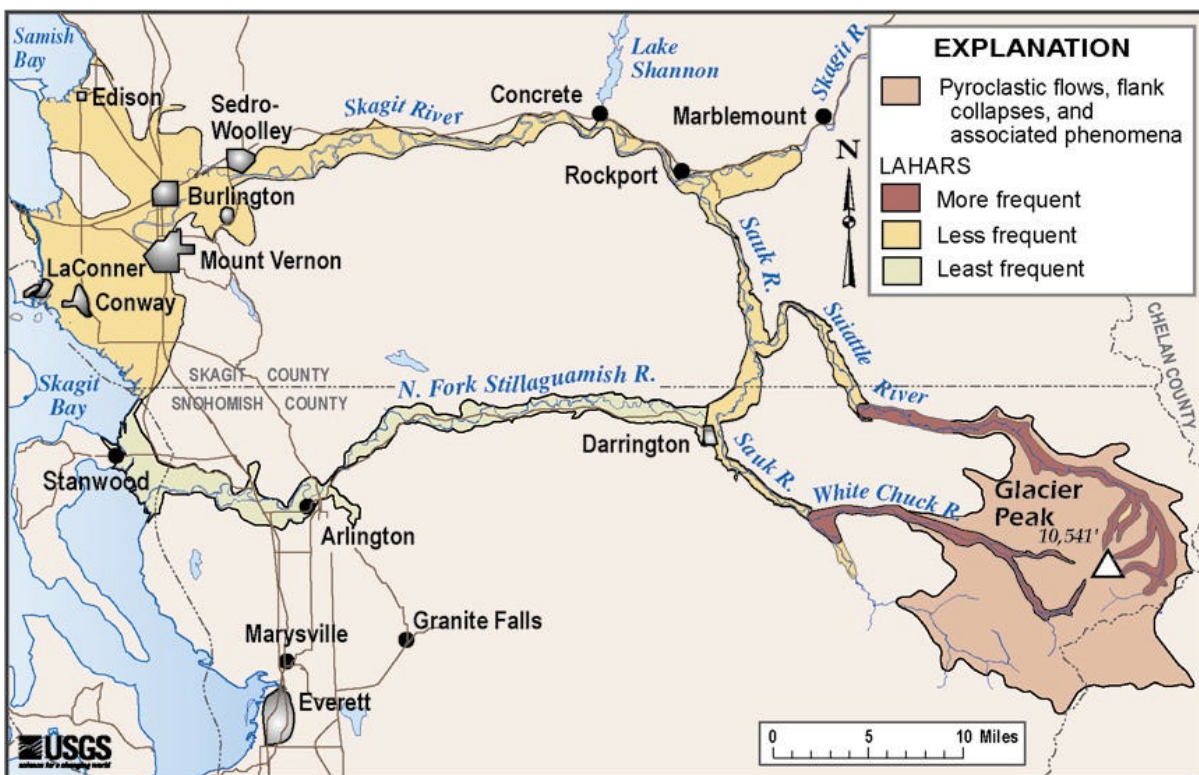
Jurisdictions Most Threatened and Vulnerable to Volcanic Hazards

The jurisdictions most vulnerable to lava flow or lahars from volcanic eruptions come from U.S. Geological Survey hazard reports and hazard zone maps published for each volcano. The hazard zone maps included in this profile only illustrate the hazard zones in a general way, and should not be used for any other purpose.

Jurisdictions most vulnerable are listed below, by volcano.

Glacier Peak

- Skagit County – Burlington, Concrete, Conway, Edison, Hamilton, La Conner, Mount Vernon, Rockport, and Sedro Woolley, plus valleys of the Suiattle, Sauk, and Skagit Rivers.
- Snohomish County – Arlington, Darrington, and Stanwood, plus valleys of the White Chuck, Sauk, and North Fork Stillaguamish Rivers.

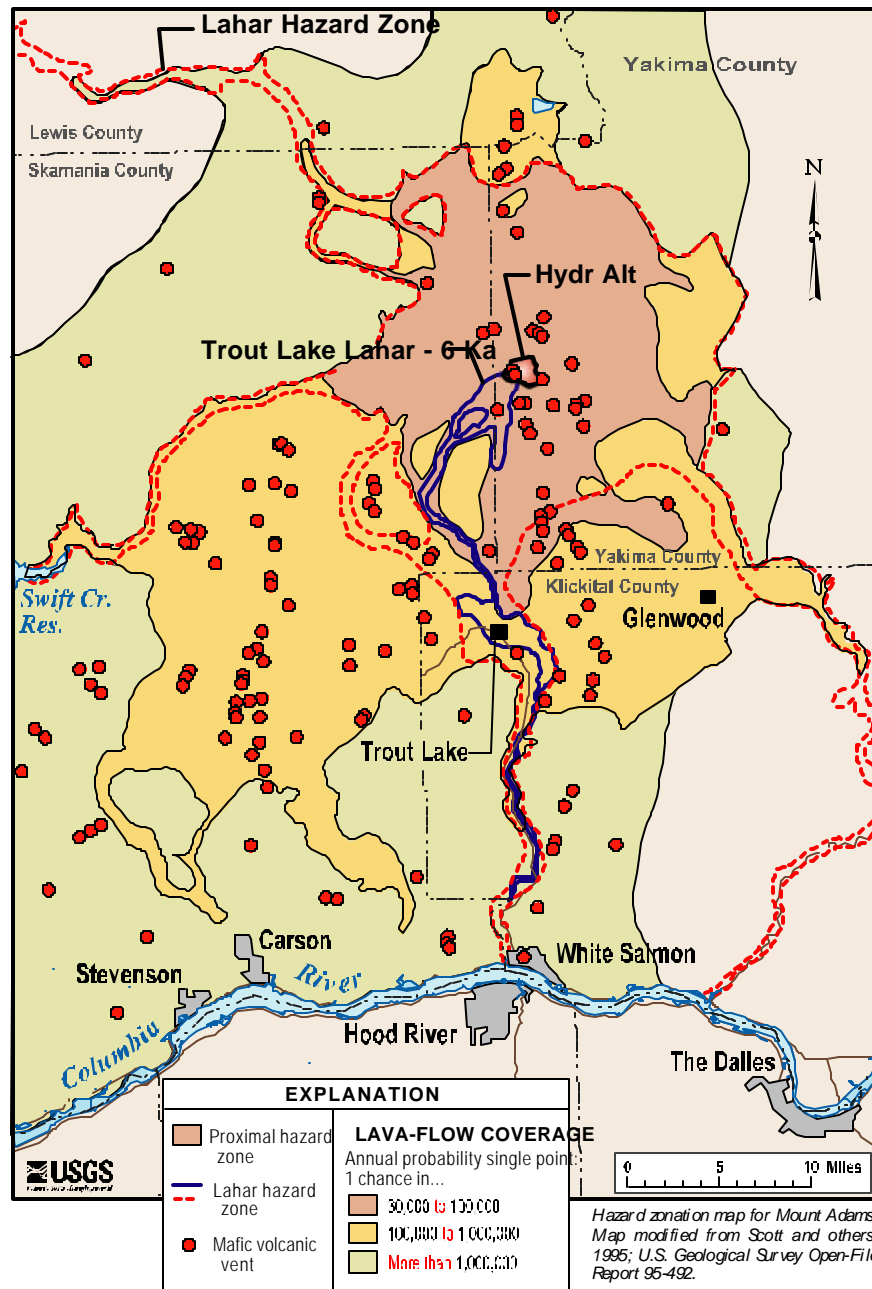


Areas at risk from lahars, lava domes, pyroclastic flows, and associated phenomena from Glacier Peak. Map modified from R.B. Waitt and others, U.S. Geological Survey Open-File Report 95-499.

Hazard Profile – Volcano

Mount Adams

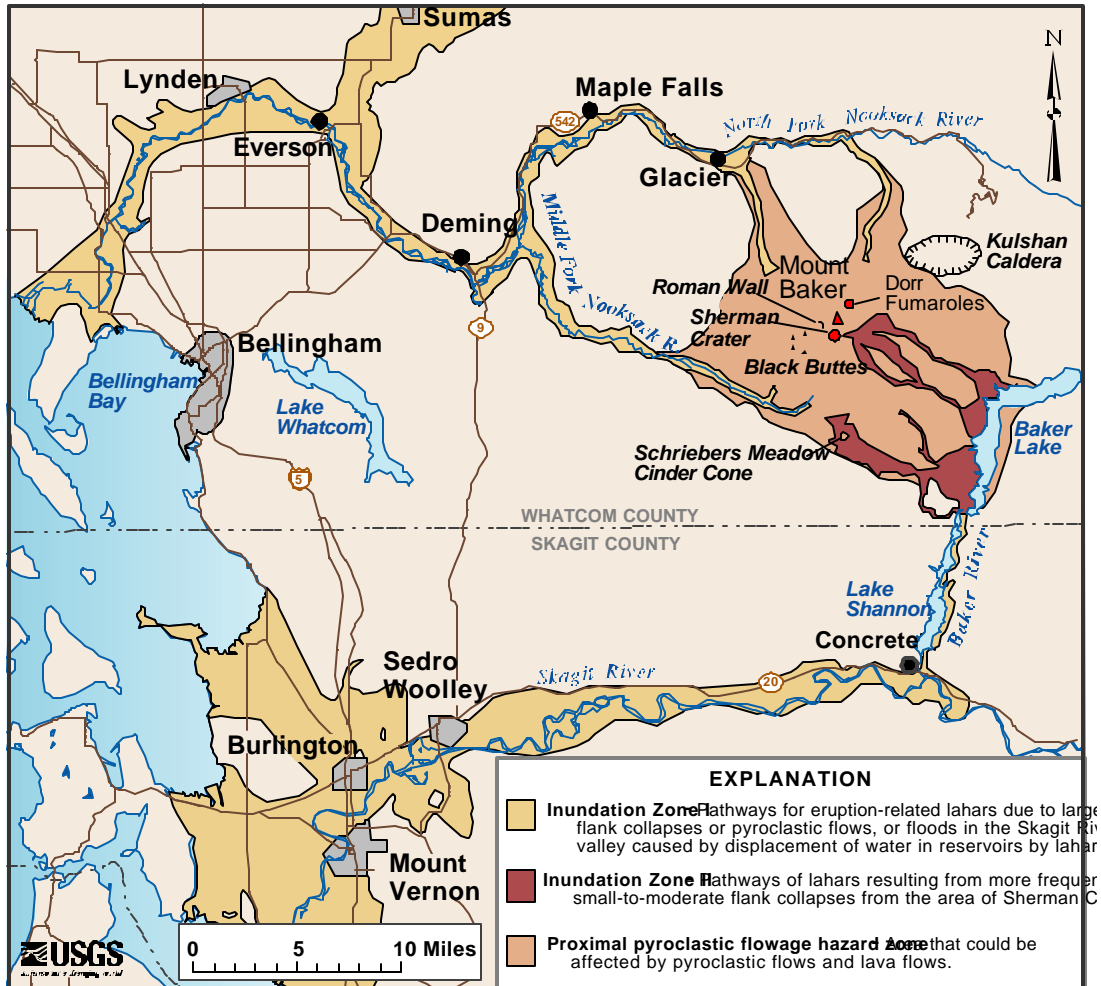
- Klickitat County – Lyle, Trout Lake and the lower White Salmon River valley.
- Skamania County – Carson, Stevenson, and unincorporated areas in the eastern part of the county including valleys of the Cispus and Lewis Rivers.
 - Numerous communities along the Columbia River in both Klickitat and Skamania Counties lie in the local proximal hazard zone for lava flow.
- Lewis County – Unincorporated areas of the Cispus River valley, including Riffe Lake.



Hazard Profile – Volcano

Mount Baker

- Skagit County – Burlington, Concrete, Conway, Edison, Hamilton, La Conner, Mount Vernon, and Sedro Woolley, and the valleys of Baker and Skagit Rivers.
- Whatcom County - Deming, Everson, Ferndale, Glacier, Kulshan, Lynden, Nooksack, and Sumas, valleys of the North Fork Nooksack, Middle Fork Nooksack, and Nooksack Rivers, and the shores of Baker Lake.

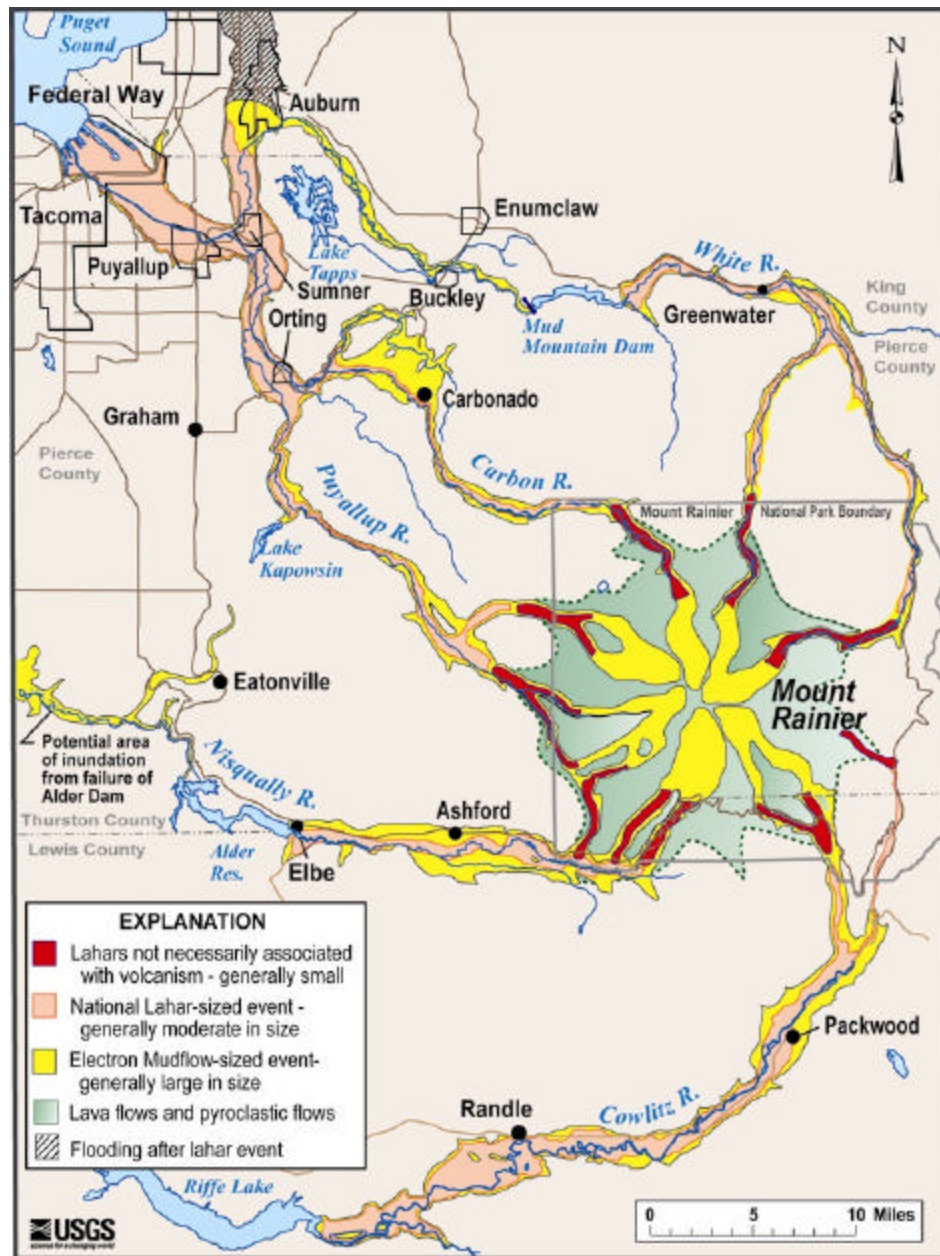


Hazard zonation map for Mount Baker. Map modified from Gardner and others, 1995; U.S. Geological Survey Open-File Report 95-498.

Hazard Profile – Volcano

Mount Rainier

- King County – Auburn, Greenwater, Kent, Pacific, Seattle (Duwamish River), and Tukwila, and the valleys of the Duwamish, Green, and White Rivers.
- Lewis County – Packwood and Randle, and the Cowlitz River valley.
- Pierce County – Ashford, Buckley, Carbonado, Elbe, Fife, McKenna, Orting, Puyallup, South Prairie, Sumner, and Tacoma, and the valleys of the Carbon, Nisqually, Puyallup, and White Rivers.
- Thurston County – The Nisqually River valley.

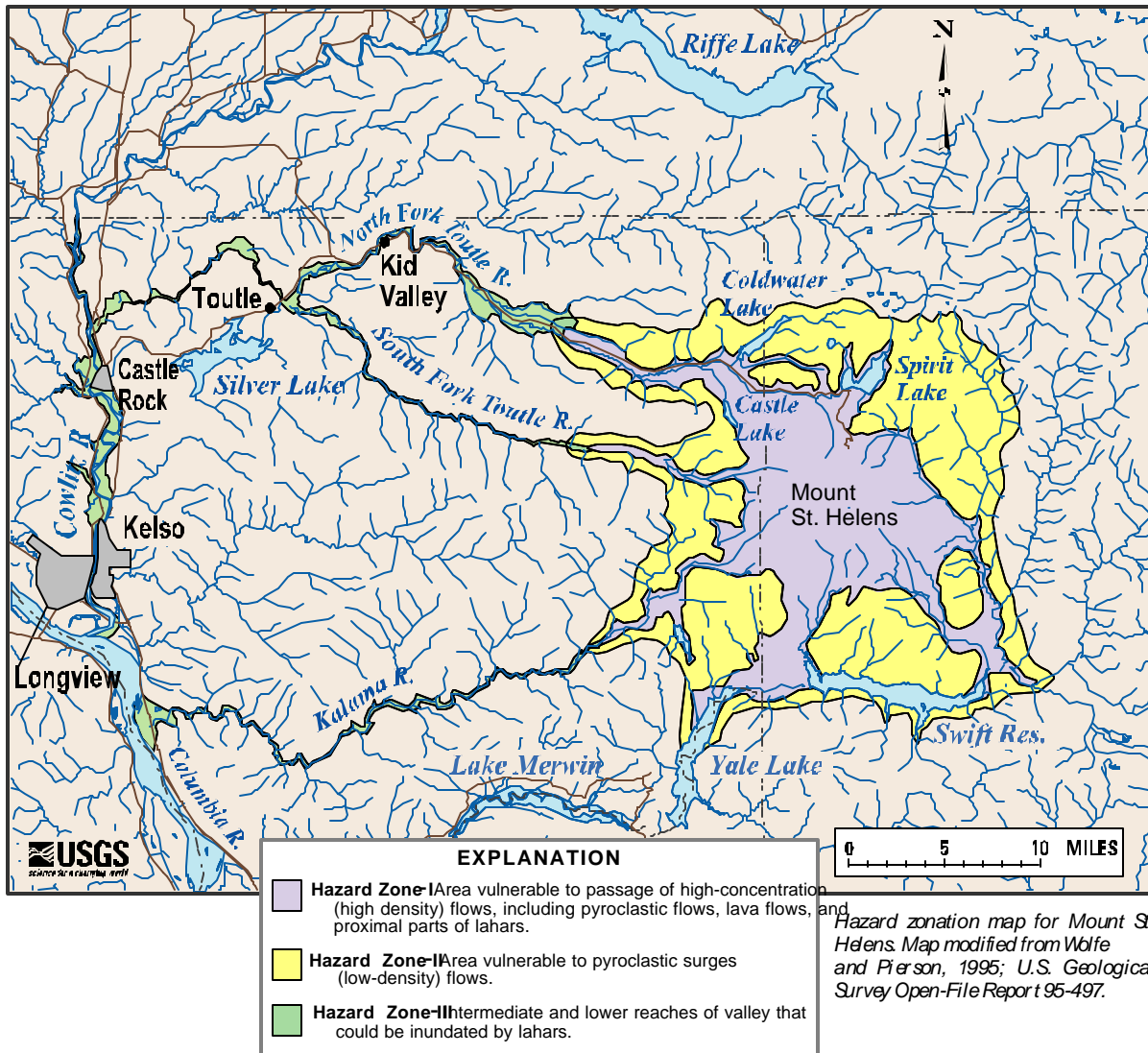


Hazard zonation map for Mount Rainier. Map modified from Hoblitt and others, 1998; U.S. Geological Survey Open-File Report 98-48.

Hazard Profile – Volcano

Mount St. Helens

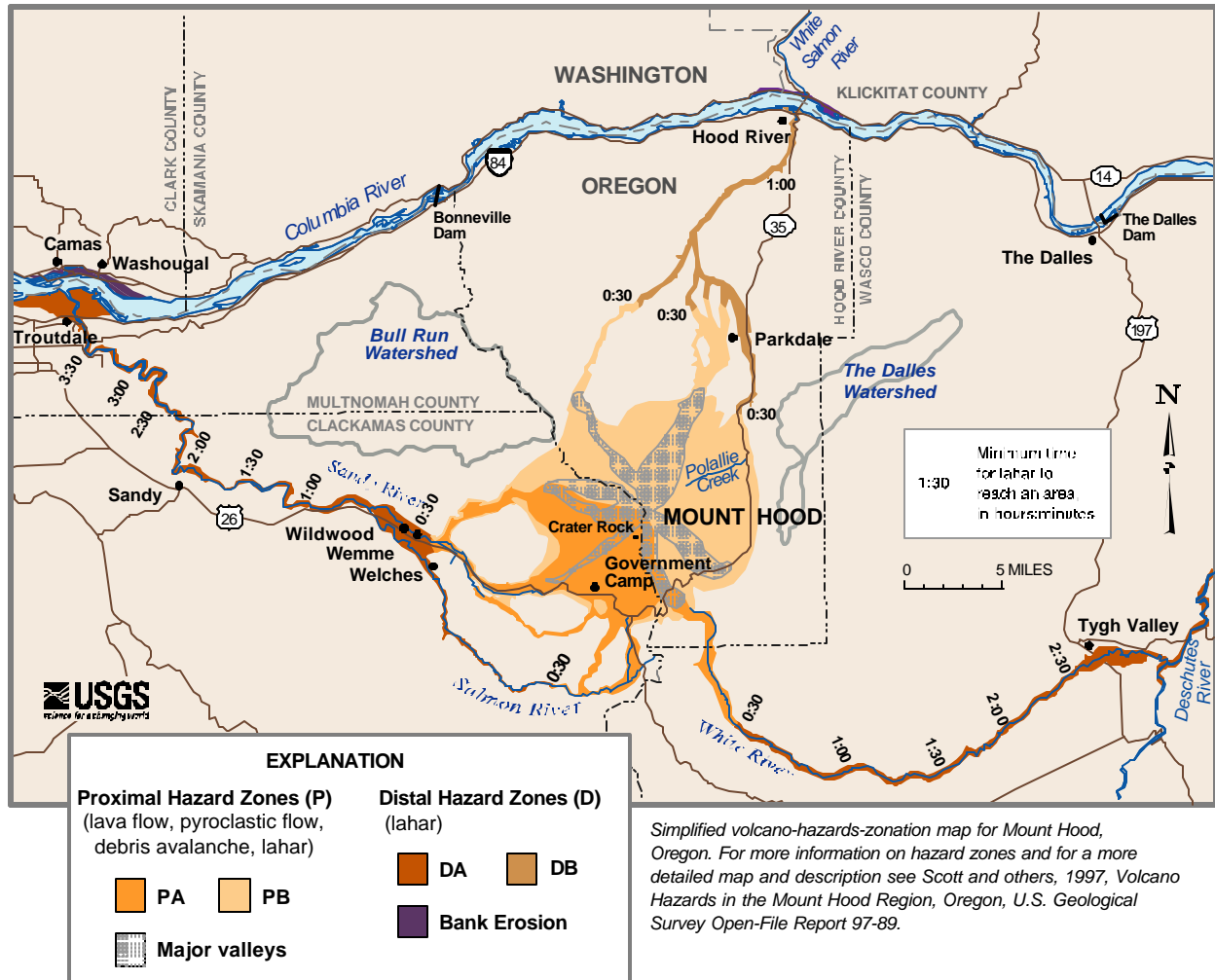
- Cowlitz County - Castle Rock, Kelso and Longview, and the valleys of the Cowlitz, Kalama, Lewis, and Toutle Rivers.



Hazard Profile – Volcano

Mount Hood, Oregon

- Clark County – Camas and Washougal, and nearby unincorporated areas.
- Klickitat County – Unincorporated areas near White Salmon.



Hazard Profile – Volcano

State Agency Structures At Risk		PRELIMINARY ASSESSMENT	
Number and Function of Buildings	No. of Affected Staff / Visitors / Residents	Approx. Value of Owned Structures	Approx. Value of Contents All Buildings
<u>Total at-risk buildings:</u> State agencies participating in this plan identified 541 facilities as being potentially at-risk to direct damage from lahar or ash fall from a volcanic eruption, or to the indirect impacts (utility services reductions, transportation restrictions, etc.).	34,308	\$1,014,274,189	\$1,125,757,023

Function of at-risk buildings: Included in the state facilities potentially at-risk to the direct and indirect impacts of volcanic eruption are the following:

- Regional headquarters, local detachments, highway weigh scales, and communication facilities of the Washington State Patrol.
- Buildings on the State Capitol Campus.
- Tacoma branch campus of the University of Washington.
- Campuses of Maple Lane School, Green Hill School, Echo Glen Children's School for juvenile offenders.
- State school for the deaf.
- Campuses of the Rainier School, Western State Hospital, and Yakima Valley School for mentally and physically disabled adults.
- Special Commitment Center for sexual offenders.
- About 150 general and client services offices that include those serving individuals and families on public assistance, providing employment and training services, driver licensing, and liquor sales.

Four state highways considered emphasis corridors because of their importance to movement of people and freight is potentially at-risk to lahar from a volcanic eruption:

1. Interstate 5
2. State Route 14
3. State Route 20
4. State Route 167

Eight state highways considered emphasis corridors because of their importance to movement of people and freight is potentially at-risk to ash fall from a volcanic eruption:

1. Interstate 82
2. Interstate 90
3. U.S. Highway 2
4. U.S. Highway 12
5. U.S. Highway 97
6. U.S. Highway 195
7. U.S. Highway 395
8. State Route 17

Hazard Profile – Volcano

<u>Total at-risk critical facilities:</u> State agencies participating in this plan identified 186 critical facilities as being potentially at-risk to direct damage from lahar or ash fall from a volcanic eruption, or to the indirect impacts (utility services reductions, transportation restrictions, etc.).	10,317	\$533,231,652	\$170,172,287
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Function of at-risk critical facilities: Included in the state facilities potentially at-risk to the direct and indirect impacts of volcanic eruption are the following:

- Regional headquarters, local detachments, highway weigh scales, and communication facilities of the Washington State Patrol.
- Buildings on the State Capitol Campus.
- Tacoma branch campus of the University of Washington.
- Buildings on the campuses of Maple Lane School, Green Hill School, Echo Glen Children's School for juvenile offenders.
- State school for the deaf.
- Buildings on the campuses of the Rainier School, Western State Hospital, and Yakima Valley School for mentally and physically disabled adults.
- About 70 general and client services offices that include those serving individuals and families on public assistance, providing employment and training services, driver licensing, and liquor sales.

Four state highways considered emphasis corridors because of their importance to movement of people and freight is potentially at-risk to lahar from a volcanic eruption:

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2. State Route 14
3. State Route 20
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Eight state highways considered emphasis corridors because of their importance to movement of people and freight is potentially at-risk to ash fall from a volcanic eruption:

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Hazard Profile – Volcano

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- ¹ Washington State 2001 Hazard Identification and Vulnerability Assessment, Washington State Military Department, Emergency Management Division, April 2001.
- ² Dan Dzurisin et al., U.S. Department of the Interior, U.S. Geological Survey, Fact Sheet 165-97 Online Version 1.0, *Living With Volcanic Risk in the Cascades*, <<http://geopubs.wr.usgs.gov/fact-sheet/fs165-97>>, (March 7, 2003).
- ³ J.J. Major, et al., *Sediment yield following severe volcanic disturbance – A two-decade perspective from Mount St. Helens*, *Geology*, September 2000, v.28 no. 9, p.819-822.
- ⁴ W.E. Scott, et al., U.S. Department of the Interior, U.S. Geological Survey, Open File Report 97-89, *Volcano Hazards in the Mount Hood Region, Oregon*, 1997.
- ⁵ Brantley and Power, *Reports from the U.S. Geological Survey's Cascades Volcano Observatory at Vancouver, Washington: Earthquake Information Bulletin*, v.17, n.1, January-February 1985, <http://vulcan.wr.usgs.gov/Glossary/Lahars/description_lahars.html>, (March 7, 2003).
- ⁶ Myers and Brantley, U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 95-231, *Volcano Hazards Fact Sheet: Hazardous Phenomena at Volcanoes*, 1995, <http://vulcan.wr.usgs.gov/Glossary/PyroFlows/description_pyro_flows.html>, (March 7, 2003).
- ⁷ Robert I. Tilling et al., U.S. Department of the Interior, U.S. Geological Survey, USGS Special Interest Publication, *Eruptions of Mount St. Helens: Past, Present, and Future*, 1990.
- ⁸ Steven R. Brantley and Bobbie Myers, U.S. Department of the Interior, U.S. Geological Survey, Fact Sheet 036-00, *Mount St. Helens – From the 1980 Eruption to 2000*, 2000.
- ⁹ Robert I. Tilling et al., U.S. Department of the Interior, U.S. Geological Survey, USGS Special Interest Publication, *Eruptions of Mount St. Helens: Past, Present, and Future*, 1990.
- ¹⁰ Richard B. Waitt et al., U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 95-499, *Volcanic-Hazard Zonation for Glacier Peak Volcano, Washington*, 1995.
- ¹¹ Written communication from William E. Scott, Scientist-in-Charge, Cascades Volcano Observatory, U.S. Geological Survey, U.S. Department of Interior, August 22, 2003.
- ¹² William E. Scott et al., U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 95-492, *Volcano Hazards in the Mount Adams Region, Washington*, 1995.
- ¹³ Written communication from William E. Scott, Scientist-in-Charge, Cascades Volcano Observatory, U.S. Geological Survey, U.S. Department of Interior, August 22, 2003.
- ¹⁴ Cynthia A. Gardner et al., U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 95-498, *Potential Volcanic Hazards from Future Activity of Mount Baker, Washington*, 1995.
- ¹⁵ R.P. Hoblitt et al., U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 98-428, *Volcanic Hazards from Mount Rainier, Washington, Revised 1998*, 1998.
- ¹⁶ C.L. Driedger and K.M. Scott, U.S. Department of the Interior, U.S. Geological Survey, Fact Sheet 034-02 Online Version 1.0, *Mount Rainier – Learning to Live with Volcanic Risk*, <<http://geopubs.wr.usgs.gov/fact-sheet/fs034-02/>>, (August 22, 2003).

Hazard Profile – Volcano

¹⁷ T.C. Pierson, *Estimated Lahar Travel Times for Lahars 10^7 to 10^8 Cubic Meters in Volume (Approaching a 'Case 1' Lahar in Magnitude) in the Puyallup River Valley, Mount Rainier, and Estimated Lahar Travel Times for Lahars 10^7 to 10^8 Cubic Meters in Volume (Approaching a 'Case 1' Lahar in Magnitude) in the Carbon River Valley, Mount Rainier*, Revised October 11, 2001, U.S. Department of the Interior, U.S. Geological Survey.

¹⁸ Edward W. Wolfe and Thomas C. Pierson, U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 95-497, *Volcanic-Hazard Zonation for Mount St. Helens, Washington*, 1995, 1995.

¹⁹ W.E. Scott, et al., U.S. Department of the Interior, U.S. Geological Survey, Open File Report 97-89, *Volcano Hazards in the Mount Hood Region, Oregon*, 1997.